

Exploring hybrid star matter at NICA and FAIR

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We discuss constraints for the equation of state of hybrid star matter which can be obtained from next generation heavy-ion collisions at FAIR and NICA. Particular emphasis is on the planned NICA facility at JINR Dubna which shall provide fixed-target and collider experiments just in the relevant energy ranges.

Neutron stars (NS) provide valuable insights into the nature of nuclear matter at densities several times beyond nuclear saturation ($n_s \approx 0.16 \text{ fm}^{-3}$) [1–3]. In particular any extreme (either small or large) value of measured neutron star observables, such as radius, mass, and temperature, is likely to improve our understanding of the properties of cold and dense matter substantially. A prime example underlining this statement is neutron star PSR J1614-2230, whose recently measured mass of $(1.97 \pm 0.04) M_\odot$ makes this object the heaviest neutron star ever observed with sufficient accuracy and confidence [4]. This measurement has direct consequences for the investigation of dense matter in terrestrial heavy-ion collision (HIC) experiments, as planned for NICA [5] and FAIR [6]. The reason for this is the close relationship that exists between the stiffness of the equation of state (EoS) of symmetric nuclear matter and the highest NS mass supported by the associated EoS for neutron star matter, as illustrated in Figs. 1 and 2 in [3]. In this paper, a testing scheme, consisting of different constraints from astrophysical observations and HIC experiments, has been introduced and consistently applied to a given set of nuclear EoS. In detail, the scheme suggests that a viable EoS should

- reproduce the most massive observed neutron star,
- avoid the direct URCA (DU) cooling problem,
- result in neutron stars within the predicted mass-radius domains of 4U 0614+09 (de-

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duced from quasiperiodic brightness oscillations) and RX J1856-3754 (deduced from the objects thermal emission),

- explain the gravitational mass and total baryon number of pulsar PSR J0737-3039(B) with at most 1% deviation from the baryon number predicted for this particular object,
- not contradict flow and kaon production data of heavy-ion collisions .

At the time of publication of Ref. [3], the most massive NS has been PSR J0751+1807 with $M \sim 2.1 M_{\odot}$, a result which has later been withdrawn [7]. A second, less strict mass constraint had been formulated, which demanded that the successful nuclear EoS reproduces at least a maximum neutron star mass of $1.6 M_{\odot}$. All the EoS investigated back then passed this constraint. Due to the precision of the new mass measurement for PSR J1614-2230, we now update the overall result of this testing scheme (analogously to Table V in [3]). It is evident from Table I that only four (five) of the formerly eight nuclear EoS are still compatible with the upper (lower) mass value measured for PSR J1614-2230. An additional model for the nuclear EOS—the hybrid EOS “DBHF-NJL”— has been included in Table I, which has several advantages over the purely hadronic EoS. Details about this EOS will be discussed below.

In summary, the important lesson that we learn from high NS masses, as measured for PSR J1614-2230, is that the EoS has to be ‘rather stiff’ or, conversely, can ‘not be too soft’ at ultra-high densities in order to be compatible with neutron star masses. In the following we point out how HIC experiments can contribute to constrain the behavior of the nuclear EoS further and, most importantly, provide most valuable information about the possible existence of quark matter in compact stars.

We focus here on two topics in HIC experiments which are relevant for determining the stiffness of nuclear matter at supersaturation densities and thus have direct implications for the astrophysics of compact stars: (i) strangeness production and (ii) transverse and elliptical particle flow.

According to the present status of the theory, subthreshold K^+ production at $E_{\text{lab}} < 1.58 \text{ A GeV}$ appears to require a sufficiently soft equation of state (see [9] and [10] for recent reviews). This is an interesting complement to the astrophysical requirement of sufficiently stiff equations of state demanded by the observations of high-mass neutron stars, as discussed above. The analysis of flow data for experiments at different energies ($E_{\text{lab}} = 0.4$ to 10 A GeV

Model	$M_{\max} \geq 2.01 M_{\odot}$	$M_{\max} \geq 1.93 M_{\odot}$	$M_{DU} \geq 1.5 M_{\odot}$	$M_{DU} \geq 1.35 M_{\odot}$	4U 1636-536 (u)	4U 1636-536 (l)	RX J1856 (A)	RX J1856 (B)	J0737 (no loss)	J0737 (loss 1% M_{\odot})	SIS+AGS flow	SIS flow+K ⁺ prod.	No. of passed tests (out of 6)
NL ρ	-	-	-	-	-	-	-	-	-	-	+	+	1 1
NL $\rho\delta$	-	-	-	-	-	-	-	-	-	-	+	+	1 1
DBHF	+	+	-	-	+	+	-	+	-	+	-	+	2 5
DD	+	+	+	+	+	+	-	+	-	-	-	-	3 4
D³C	+	+	+	+	+	+	-	+	-	-	-	-	3 4
KVR	-	-	+	+	-	o	-	-	-	+	+	+	2 4
KVOR	+	+	+	+	-	+	-	-	-	o	+	+	3 5
DD-F	-	+	+	+	-	+	-	-	-	+	+	+	2 5
DBHF+NJL	+	+	*	*	+	+	-	+	-	+	+	+	4 6

TABLE I: Summary of results for the testing scheme suggested in [3], updated by the recently measured mass of PSR J1614-2230 ($(1.97 \pm 0.04) M_{\odot}$) and supplemented by the hybrid EoS of Ref. [8] (DBHF-NJL, last line), for which results are shown in Fig. 1. EoS not labeled in bold face fail to reproduce a NS mass of $2.01 M_{\odot}$. Non-separated columns show the results for a strict (left) and weakened (right) interpretation of the corresponding constraint. The last column gives the total number of tests passed by a given EOS. (For details, see [3].)

in Ref. [11]) put a constraint on the cold symmetric nuclear EoS, which represents a region in the nuclear pressure-density plane, $P(n)$, shown in Fig. 1. This constraint is readily applied to the isospin-symmetric part of any neutron star EoS and can therefore be used to derive upper bounds on the maximum mass of compact stars [3], as can be seen by comparing the left and right panels of Fig. 1. From the latter constraint it is evident that an independent confirmation of this flow constraint is very important, both theoretically as well as experimentally by providing sufficiently accurate flow data in the region of $E_{\text{lab}} \sim 1$ to 5 A GeV (Nuclotron fixed-target range), where we suspect the deconfinement phase transition to occur, and just above the limits of the AGS data range, i.e. for $E_{\text{lab}} = 10$ to 60 A GeV (CBM range and fixed-target equivalent of the NICA collider range). According to the flow constraint, the *ab-initio* DBHF EoS, computed for the Bonn-A nucleon-nucleon

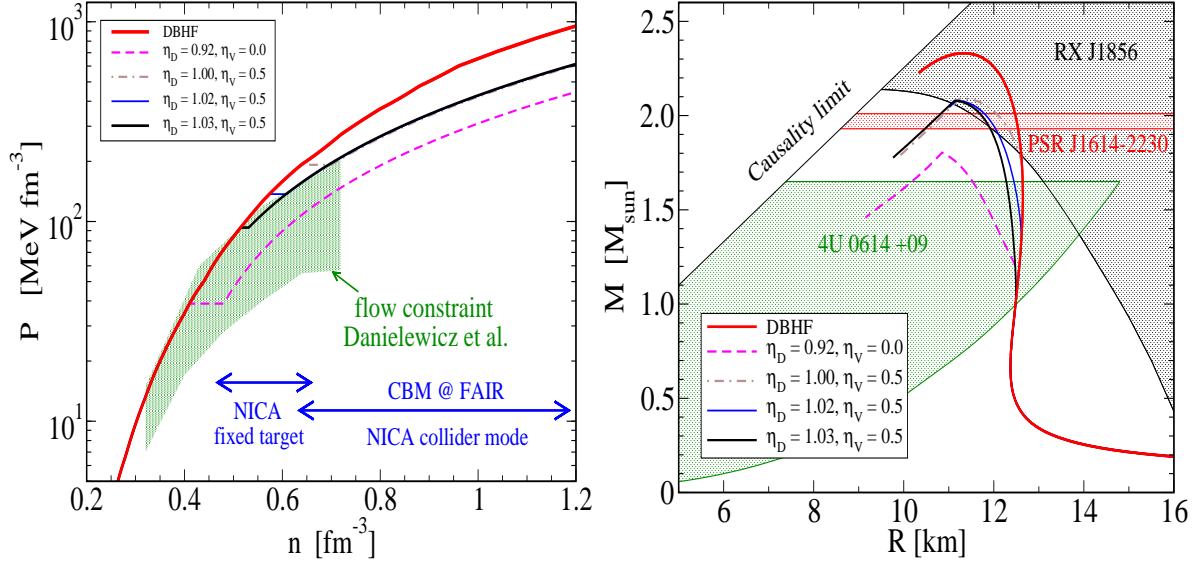


FIG. 1: Left panel: Flow constraint [11] extracted from HIC experiments in the range $E_{\text{lab}} = 0.4$ to 10 A GeV and estimated regions accessible at CBM and NICA experiments [12, 13]. Right panel: Sequences of compact star M-R relations obtained from solution of the Tolman-Oppenheimer-Volkoff [1, 2] equation for different EoS without (DBHF) and with deconfinement transition, as compared to NS constraints.

potential, appears to be too stiff at densities above 3.5 times saturation density. Assuming the deconfinement phase transition to provide the softening of the high-density EoS just in this density range and at the maximally tolerable stiffness of the Danielewicz *et al.* constraint would result in an upper limit for the maximum mass of compact stars at $2.1 M_{\odot}$ [3, 8]. This is compatible with the new mass constraint provided by PSR J1614-2230. The quark matter EoS used here is the three-flavor color superconducting NJL model with self-consistently determined masses and diquark gaps [14], including a vector meson meanfield which entails a sufficient stiffening of the hybrid EoS [8] (a nonlocal, covariant generalization has been provided in Ref. [15]). Neglecting the latter term would result in a too soft hybrid EoS, conflicting with the new neutron star mass constraint (dashed lines in Fig 1). Moreover, if the diquark pairing interaction would be sufficiently reduced or even be neglected altogether so that no color superconducting phase can occur, the phase transition would occur at densities too high to be realized even within the most massive NS.

Due to isospin asymmetry, in compact stars the deconfinement transition always occurs at lower baryon densities than in symmetric nuclear matter. There is another, indirect

argument to expect a deconfinement phase transition in symmetric matter at densities not exceeding about 3 to 4 nuclear saturation densities. This relatively low critical density would correspond to a deconfinement transition before the onset of hyperon formation. This is a possible solution to the problem that hyperon EoS are often too soft to fulfill the maximum-mass constraints, see Ref. [16]. In addition, a sufficiently low onset density for quark matter avoids the DU problem of the DBHF EoS which otherwise would lead to a too fast cooling of neutron stars with masses in the typical binary radio pulsar range $1.3 \leq M/M_\odot \leq 1.4$.

As valuable as the analysis of NS observables and the evaluation of kaon production and flow data appears, presently applied model EoS for hybrid matter suffer from the artificial description of the hadron-to-quark matter phase transition. Two-phase approaches, using Maxwell or Glendenning constructions [17], cannot make trustworthy statements about the phase transition region, and only estimate the region of a transition very roughly. In general, these constructions describe only first order transitions. Therefore, any statement about the critical endpoint in the phase diagram which results from corresponding models is, at best, an estimate. More elaborate treatments applying functional renormalization group methods are promising [18] but have to be extended to include the baryons. Even then they will be lacking to describe aspects resulting from the compositeness of baryons such as the existence of a scattering continuum of three- and multi-quark states at finite densities which entails the dissociation of baryons into their quark constituents [19]. A generalized Beth-Uhlenbeck EoS [20, 21] which accounts for these effects is presently being developed [22].

In conclusion, the question whether quark matter exists in compact stars is very challenging [23] and closely related to the question of deconfinement in heavy-ion collisions at CBM [24] and NICA [13]. As we don't know a priori the coupling strengths in various interaction channels at high densities, it is important to test the conjectured EoS in a heavy-ion collision experiment. The energies provided at the NICA facility (both fixed target and collider) are perfectly suited for providing astrophysically relevant constraints. Without further necessary experimental evidence as will be provided, e.g., from NICA or FAIR one cannot safely rule out or support the possibility that all neutron stars in the observed mass range between 1.23 and $2.01 M_\odot$ are hybrid stars with quark matter cores!

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